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PHOSPHATE REMOVAL BY ACTIVATED SLUDGE

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U.S. DEPARTMENT OF THE INTERIOR
FEDERAL WATER POLLUTION CONTROL ADMINISTRATION
ROBERT S. KERR WATER RESEARCH CENTER
ADA, OKLAHOMA

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by

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INTRODUCTION

Phosphate removal has exceeded 80 percent during treatment of domestic-industrial wastes in diversely located activated sludge plants. Unusually high phosphate reductions were correlated with design and operation of the activated sludge process. Determination of the design and operational conditions resulting in consistent high-level phosphate removals was the goal of a series of field investigations which are summarized in this paper.

Initial field investigations at three plants operated in parallel (Rilling, West, and East) in San Antonio, Texas, were 10 weeks in duration. Initially, the Rilling Plant was studied most intensively; later considerable effort was expended on the West Plant. The investigation at San Antonio showed that, for two years prior to the studies, phosphate removal had averaged 80 percent in the Rilling Plant and that higher removal was possible. To determine the applicability of the process to other wastes and locations, 13 additional plants were monitored from one to two weeks each. During plant monitoring, bench-scale batch studies showed that three-fourths of the wastes and activated sludges were amenable to phosphate removal under improved operating conditions.

In addition to the Rilling Plant, four plants were accomplishing high phosphate removal. Additional 10-day investigations, carried out on these four plants, included a total phosphate balance and

round-the-clock monitoring. Data from the five removing plants demonstrate that the activated sludge process can result in high phosphate reroval efficiencies on diverse domestic-industrial waste mixtures. The designs and operating conditions of these five plants have striking similarities.

GENERAL CASE OF PHOSPHATE REMOVAL

Figure 1 is presented to illustrate the most common conditions in an activated sludge plant removing phosphate. Figure 1 is a combination of an activated sludge schematic diagram and a phosphate* concentration curve. Orthophosphate concentration versus location in the schematic is presented by using a common abscissa.

The figure presents a summary of information gathered from the field investigations. From left to right, the indications are: There is little, if any, change in orthophosphate through the primary clarifier. (A decrease in total phosphate has been measured in some clarifiers.) The mixing of return sludge and primary effluent results in an orthophosphate concentration in excess of either the components or a calculated mixture concentration. This results from a release of phosphate from the sludge to solution.

The most diverse aeration tank conditions are shown as Case I and II. Case I usually occurs when the waste flow and strength are greatest. The orthophosphate concentration increases up to half the length of the tank followed by removal in the remaining

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*Phosphate and orthophosphate are used as synonyms; total phosphate is specified.

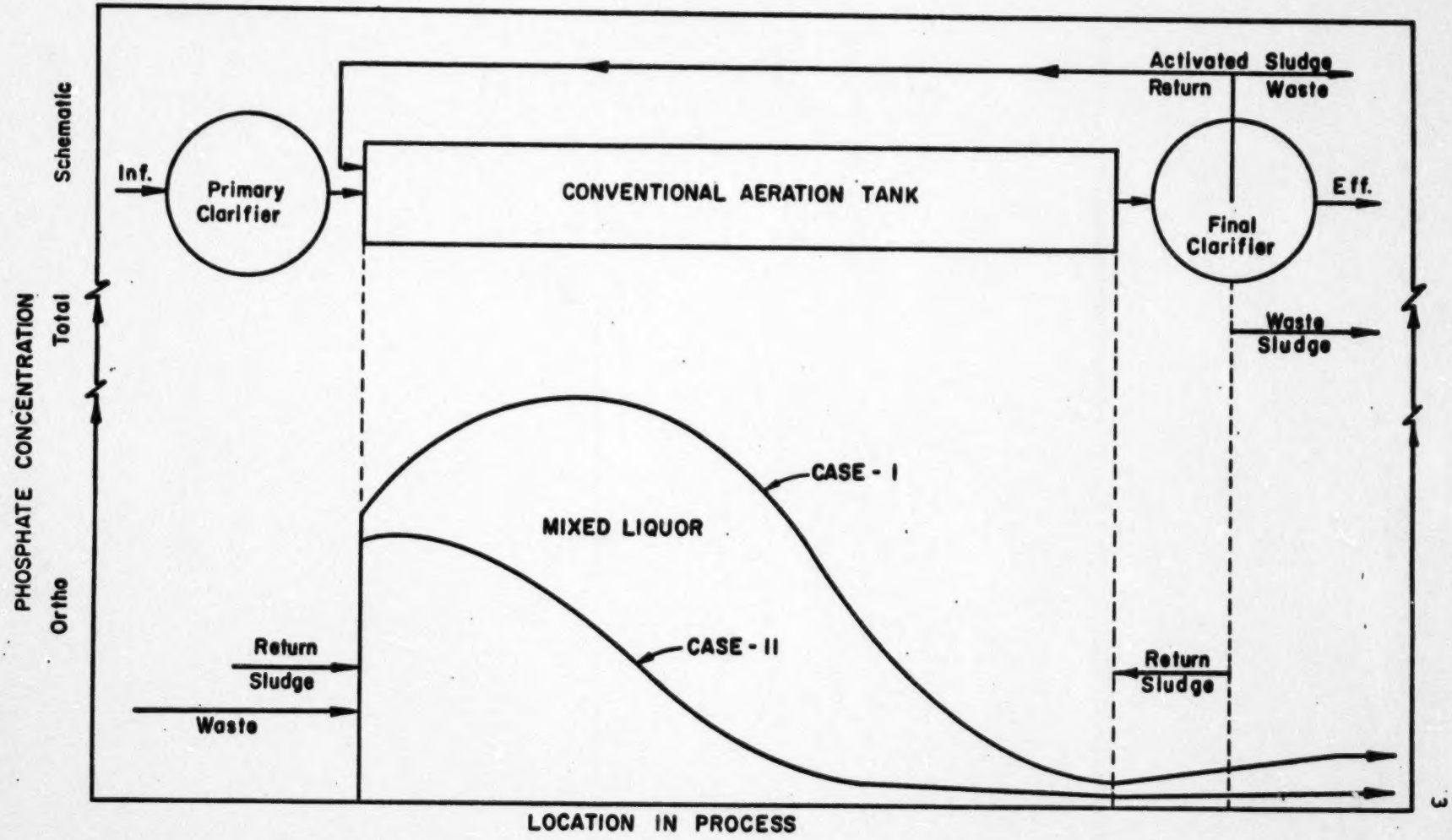

FIGURE I - PHOSPHATE CONCENTRATION THROUGH ACTIVATED SLUDGE PROCESS

tank volume. Case II usually occurs when the waste flow and strength are minimum. The phosphate concentration decreases in the first portion of the aeration tank; less than 1.0 mg/l has been measured by the midpoint of the tank. Both Case I and II indicate that phosphate uptake is time dependent and related to the time of retention of the mixed liquor under aeration.

Increases in orthophosphate concentration can be minimized in the final clarifier by efficient operation. The phosphate has been removed by incorporation in the sludge solids. Efficient solid-liquid separation and minimum sludge detention are critical to affect removal of the phosphate-laden solids before phosphate is released to the final effluent.

The vehicle for disposal of the phosphate is the waste activated sludge. The waste sludge releases phosphate under anaerobic conditions and can not be recycled or the process becomes a closed loop and is destroyed.

Figure 1 represents a general case of an activated sludge plant with high phosphate removal. Variations from the general case found in the plants studied and specific data supporting the general case follow.

PROCESS REMOVAL

The Baltimore Back River Plant and the San Antonio Rilling Plant have the longest records showing phosphate removal by the activated sludge process.

Two investigations at Baltimore showed 90 percent phosphate removal. During the initial 10-day study, 30 grab samples of primary effluent and final effluent were analyzed for orthophate. The data are summarized in Table I. Three-fourths of the final effluent samples contained 0.1 mg/l-P or less orthophosphate. During the second study, 24-hour composite samples of the primary effluent and final effluent were collected for a month. These samples were analyzed for total phosphate at the Robert A. Taft Water Research Center. The data are also summarized in Table I.

TABLE I. PHOSPHATE CONCENTRATION (mg/l-P)

Item	Study 1 Orthophosphate		Study 2 Total Phosphate	
	Prim. Eff.	Final Eff.	Prim. Eff.	Final Eff.
Average	8.5	0.8	10.6	1.0
Minimum	5.3	<0.1	5.6	0.2
Maximum	12.0	9.7	16.3	3.8

The two studies, which were separated by 13 months, establish a month of high level removal by the activated sludge process and suggest continuous phosphate removal.

In San Antonio, there were about two years of orthophosphate data on daily composite samples of raw waste and final effluent. Since orthophosphate concentrations in the raw waste and primary effluent were identical in the Rilling Plant, the difference in

concentration between the raw and final effluent was accomplished by the activated sludge process. From two hundred daily records picked at random, a frequency diagram of removals was constructed (Figure 2). Fifty percent of the records had phosphate removal of 85 percent or more, 75 percent removal occurred 25 percent of the time. A continuous and sustained phosphate removal process was established.

Total phosphate balances were made on the five activated sludge processes wherein grab sampling had indicated high levels of phosphate removal. Composite samples of the primary effluent, final effluent, and waste sludge were collected daily and analyzed for total phosphate. An inventory of phosphate in the units was made at the beginning and end of the balance period. The values were obtained from plant meters or gauge records. These data are summarized in Table II.

Total phosphate removal efficiency was from 71 to 79 percent in the five activated sludge processes. The selection of study periods, controlled by the availability of research personnel, resulted in monitoring during operational difficulties at two plants. The range in removal reflects variable conditions in plants neither designed nor operated for phosphate removal.

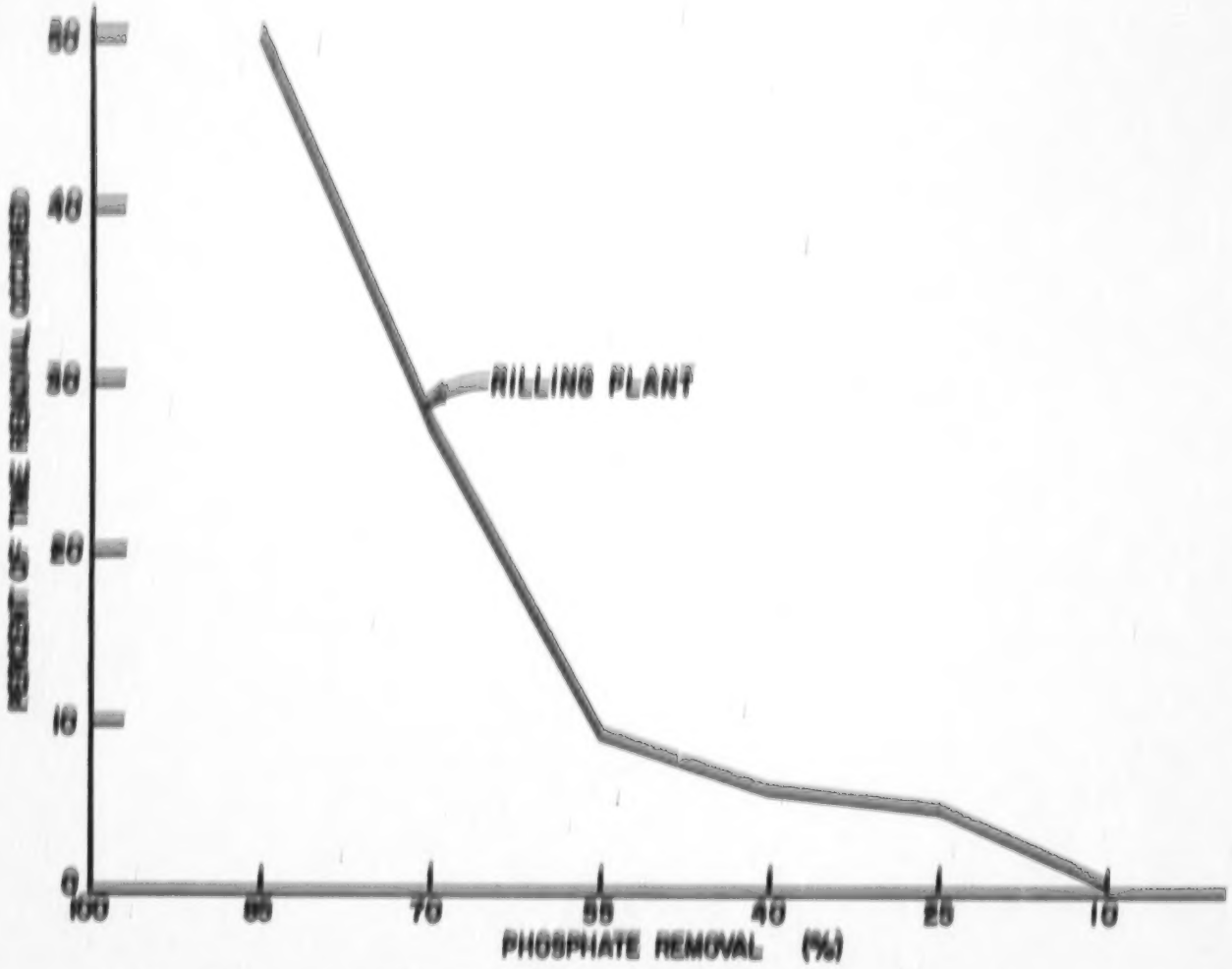

FIGURE 2 - REMOVAL FREQUENCY - SAN ANTONIO, TEXAS

TABLE II. TOTAL PHOSPHATE BALANCE IN ACTIVATED SLUDGE PROCESS

Location Plant	Days Sampled	PERCENT IN PRIMARY EFFLUENT Removed in Final Eff.	Accounted For	Discharged in Sludge
San Antonio, Texas				
Rilling	6	72	73	53
West	9	75	115	75
Fort Worth, Texas				
Village Creek	7	74	132	94
Village Creek	10	57	103	46
Baltimore, Maryland				
Back River	11	72	55	37
Amarillo, Texas				
Northside	10	51	85	36

Except for Baltimore, total phosphate accounted for by the measurement techniques were within 30 percent of unity. The Baltimore balance was seriously affected by flow meters which were out of adjustment. On several days, computed quantities of sludge wasted were negative.

In a perfect balance where the tank inventory did not change, the percent phosphate removed in the final effluent should equal that discharged in the waste sludge. Except for Baltimore, these values were within 20 percent; thereby, establishing the waste sludge as the vehicle for phosphate disposal. The waste sludge solids averaged 6 percent P on a dry-weight basis.

OPERATIONAL EFFECTS

The Rilling Plant and the West Plant in San Antonio were both conventional activated sludge plants. Phosphate and standard

performance data were available for most of 1964 and 1965 on both plants. Two hundred daily records containing complete data on fifteen parameters were randomly selected for both plants. Several operational parameters were computed and the mean, variance, and type of distribution determined for all parameters. The mean phosphate removals were 30 percent in the West Plant and 80 percent in the Rilling Plant. Examination of the data suggested the existence of other significant differences. Statistical hypothesis tests were made except where the variances of the parameters were too heterogenous for validity. The results are shown in Table III.

TABLE III. MEAN CONCENTRATION AND DIFFERENCE AT 0.05 LEVEL

Item	West	Rilling	Significant
Influent (mg/l)			
BOD	179	185	No
TSS	119	121	No
MLSS	959	1,289	Yes
Effluent			
BOD	23	27	No
TSS	11	11	No
NH_3-N	5.2	6.7	No
NO_3-N	2.1	1.4	Yes
PO_4-P	6.3	2.0	Yes
Loadings			
Air (ft^3/gal)	2.0	1.6	Yes
BOD (#/10^3 ft^3)	31.7	34.8	Yes
Flow (mgd)	29.7	23.3	Yes

There were no significant differences in concentrations of biochemical oxygen demand (BOD) or total suspended solids (TSS) in either the influent or effluent from the activated sludge process.

to utilize the air supply in the more efficient diffusers in Tanks 7 through 12.

The operational changes affected the MLSS and dissolved oxygen concentrations in the aeration tank, the hydraulic and organic loading, the solids-liquid separation in the final clarifier, and, most significantly, the phosphate removal.

The increased solids concentration in the mixed liquor and separation efficiency in the clarifiers can be seen in Figure 3. During the study, the MLSS increased from 900 to 1,800 mg/l while the solids concentration in the final effluent gradually decreased. At the end of the study, large amounts of solids were wasted to lower the MLSS concentration.

The phosphate data plotted on Figure 3 show a gradual reduction of concentration in the final effluent after the operation was changed, followed by a marked decrease from 7.3 to 0.0 mg/l after aluminum sulfate. Tanks Nos. 8 and 9 were removed from service, and the mixed liquor solids were sharply increased. Concentrations of orthophosphate in the waste are shown for comparison.

The three aeration tanks were monitored on a plug flow basis at the beginning, middle, and end of the experiment. The curves in Figure 4 demonstrate that the first aeration tank passed from an aerobic condition of low removal (49 percent) to an intermediate condition (85 percent) after 7 days and, finally, to a state of high removal (99 percent) after 9 days of changed operation.

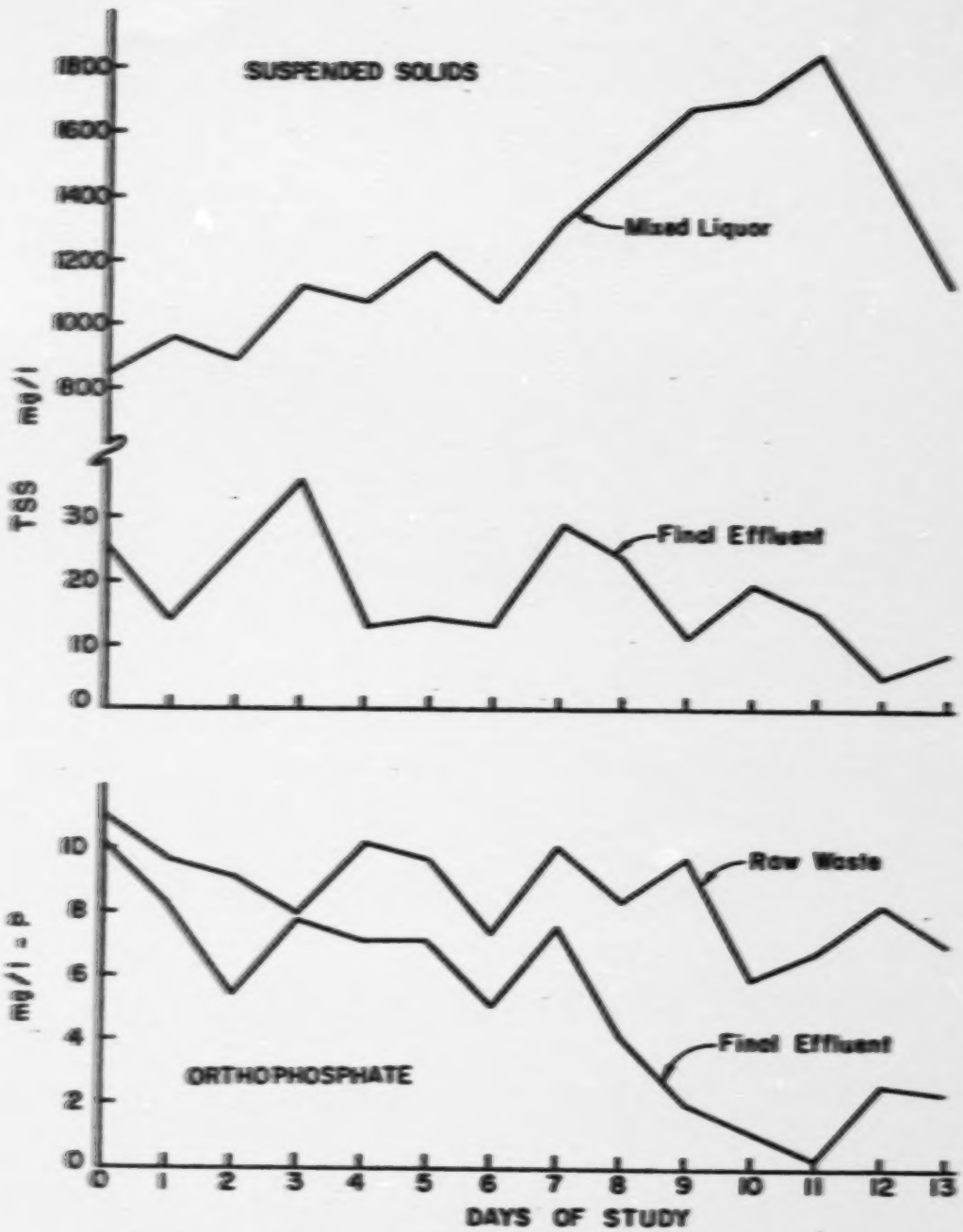

FIGURE 3 - EFFECTS OF OPERATIONAL CHANGE ON WEST PLANT

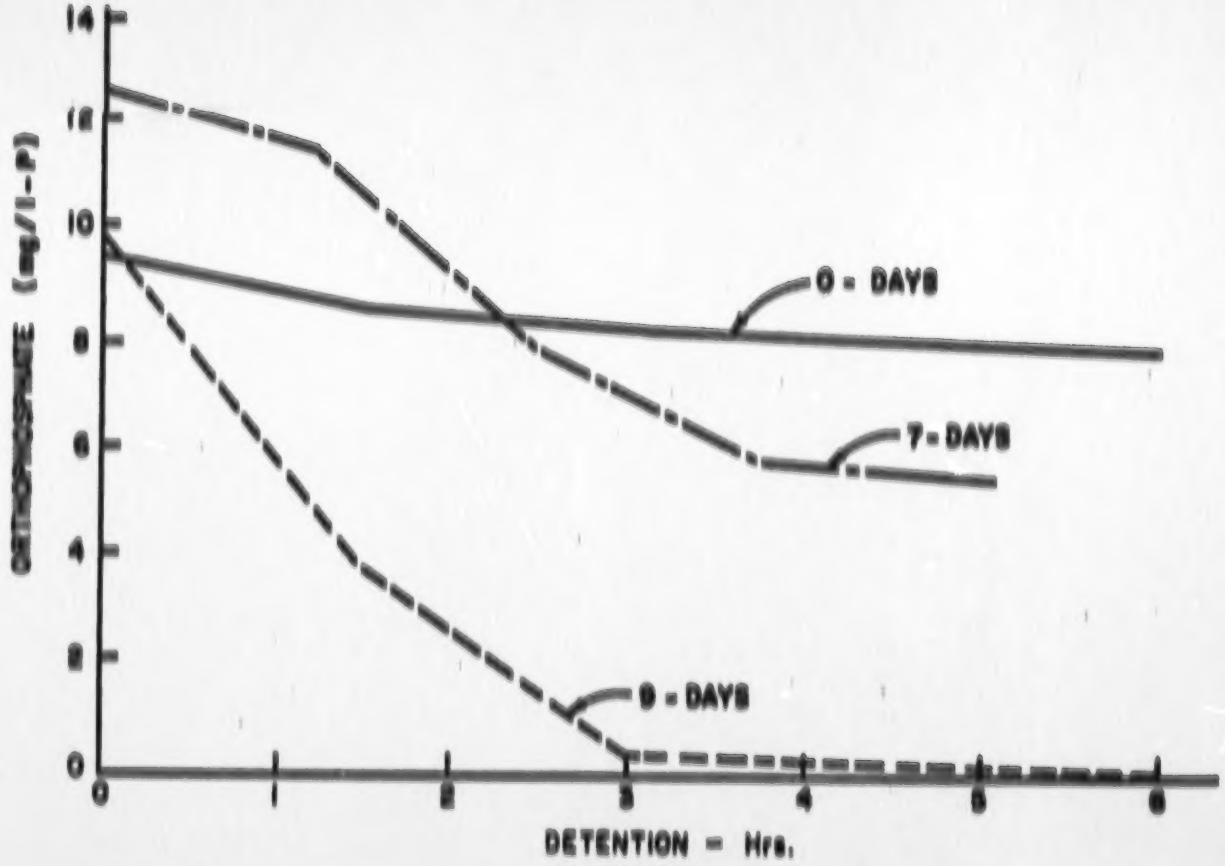

FIGURE 4 - PHOSPHATE REMOVAL - WEST AERATION TANK

Unfortunately, it was necessary to terminate the experiment by returning the plant to initial operating conditions before the polyelectrolyte was expended. Sludge wasting was increased on the 11th day to lower the MLSS level, and polyelectrolyte addition was stopped on the 13th day; however, from the 8th to the 13th day, the West Plant had 80 percent phosphate removal based on 24-hour composite samples. The effect of operational controls on phosphate removal was demonstrated.

UNIT OPERATIONS

Primary Clarifier

Phosphate removal by primary clarification is typified by the data shown in Table IV. A 24-hour profile of total and orthophosphate concentration in the Rilling raw waste and primary effluent (PE) showed no change in the concentrations through the clarifiers; therefore, raw waste was sampled only occasionally in subsequent investigations. Nine months of daily composite samples at the Cleveland Easterly plant indicated minimum removals in the primary clarifier. At Fort Worth, however, 7-day composite samples indicated significant total phosphate removal; orthophosphate concentrations were not measured. The samples taken at other plants generally showed change in concentration through the primary clarifier similar to the Cleveland data shown in Table IV.

Phosphate removal in the primary clarifiers was practically nonexistent and was insignificant to the low effluent concentrations obtained in the removing plants.

TABLE IV. PRIMARY CLARIFIER REMOVAL

LOCATION	SAMPLING	Average Phosphate Concentration (mg/l-P)			
		TOTAL		ORTHO	
		Raw	PE	Raw	PE
San Antonio	24-hr. profile	9.1	9.0	7.0	7.6
Cleveland	9-mo. composites	7.4	6.2	3.8	3.4
Fort Worth	7-day composites	17.3	11.1	--	--

Aeration Tanks

Phosphate removal is accomplished in the aeration tank. This is the key unit process for phosphate removal by activated sludge; therefore, it has received the most study. Three types of studies have been made at plant sites. Batch studies of 15 liters of mixed liquor were used to control inputs and operating conditions not feasible in the plant. Aeration tank performance studies were conducted by scheduling samples in proportion to the displacement time between points along the tank. Round-the-clock studies over a 10-day period were made on aeration tanks in four removing plants.

The importance of mixed liquor detention and the statistical difference in the inputs (waste flow and strength, amount of sludge solids, and air volume) influenced these investigations. Operational and design limits were of primary concern in these investigations because their application in other plants and in the design of treatment facilities could effectively decrease effluent phosphate concentrations.

In batch aeration studies, one parameter was varied while the others were held constant. Mixed liquors from the aeration tanks or combinations of waste and return sludge were aerated and monitored for several hours.

Figure 5 shows phosphate concentration versus aeration time at three levels of air input--0.5, 2.5, and 5.0 l/min. Primary effluent and return sludge from the Rilling Plant were mixed to obtain a TSS concentration of 1,800 mg/l. Phosphate removal increased with increased air volume.

Figure 6 shows phosphate removal versus MLSS concentration using waste and sludge from four plants. Phosphate removal increased with increased MLSS concentration to an optimum level. The optimum varied between 2,000 and 4,000 mg/l.

Figure 7 is a plot of orthophosphate concentration versus aeration time which shows the effect of waste strength on phosphate removal. Phosphate and BOD concentrations were the constituents varied. The upper graph illustrates the effect of BOD at a MLSS concentration of 1,860 mg/l. The relative amount of BOD as shown in Figure 7, varies from 1/4 to 3 times the control. The BOD of the waste was increased by adding Metrecal* and decreased by diluting with plant effluent.

The lower graph shows the effect of phosphate concentration on removal. The relative amount of phosphate in the waste is also shown on the figure. The phosphate was supplemented by

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*Mention of product is for identification only and does not imply endorsement by the FWPCA or the USDI.

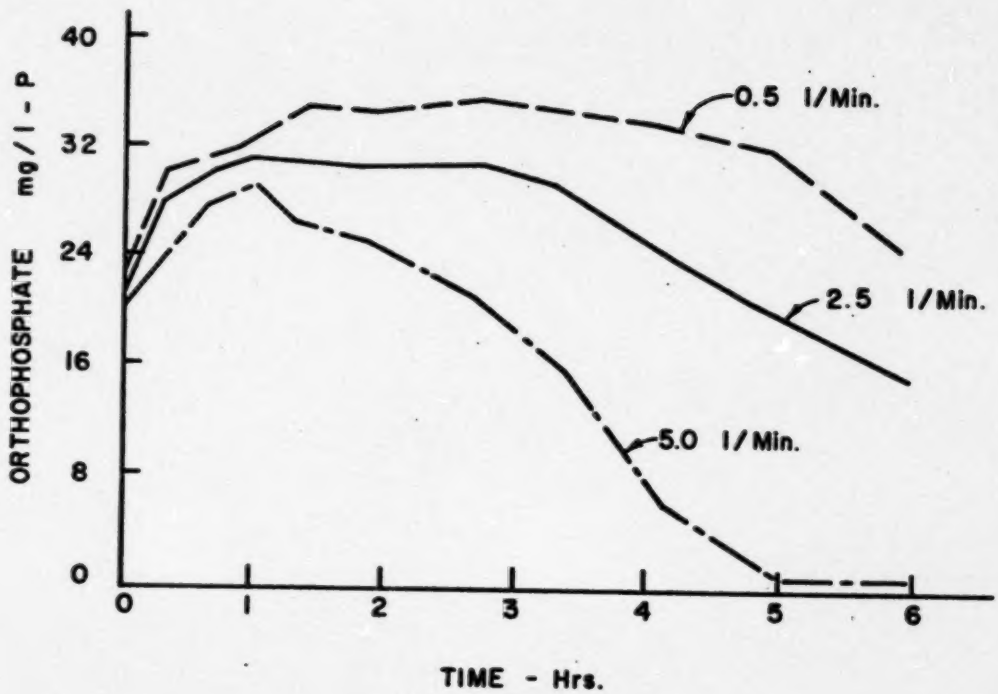

FIGURE 5 - EFFECT OF AIR VOLUME ON PHOSPHATE REMOVAL

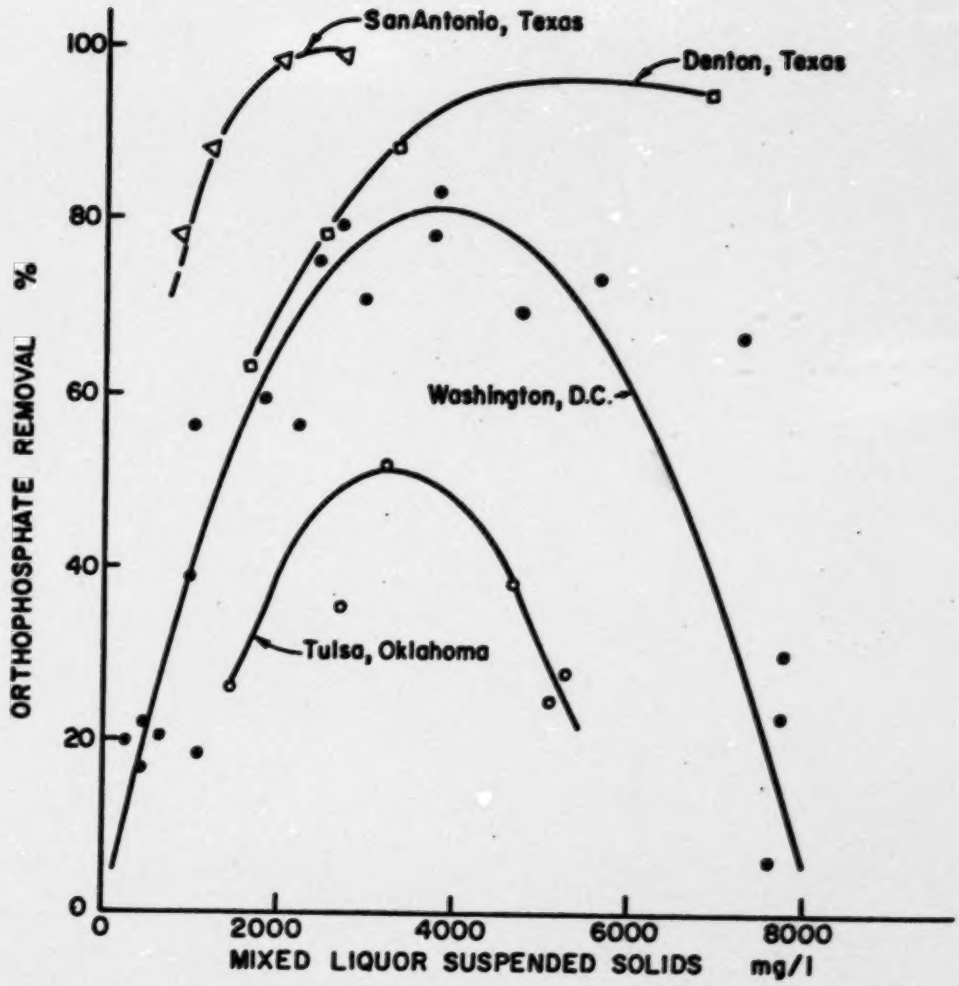

FIGURE 6 - EFFECT OF MLSS ON PHOSPHATE REMOVAL

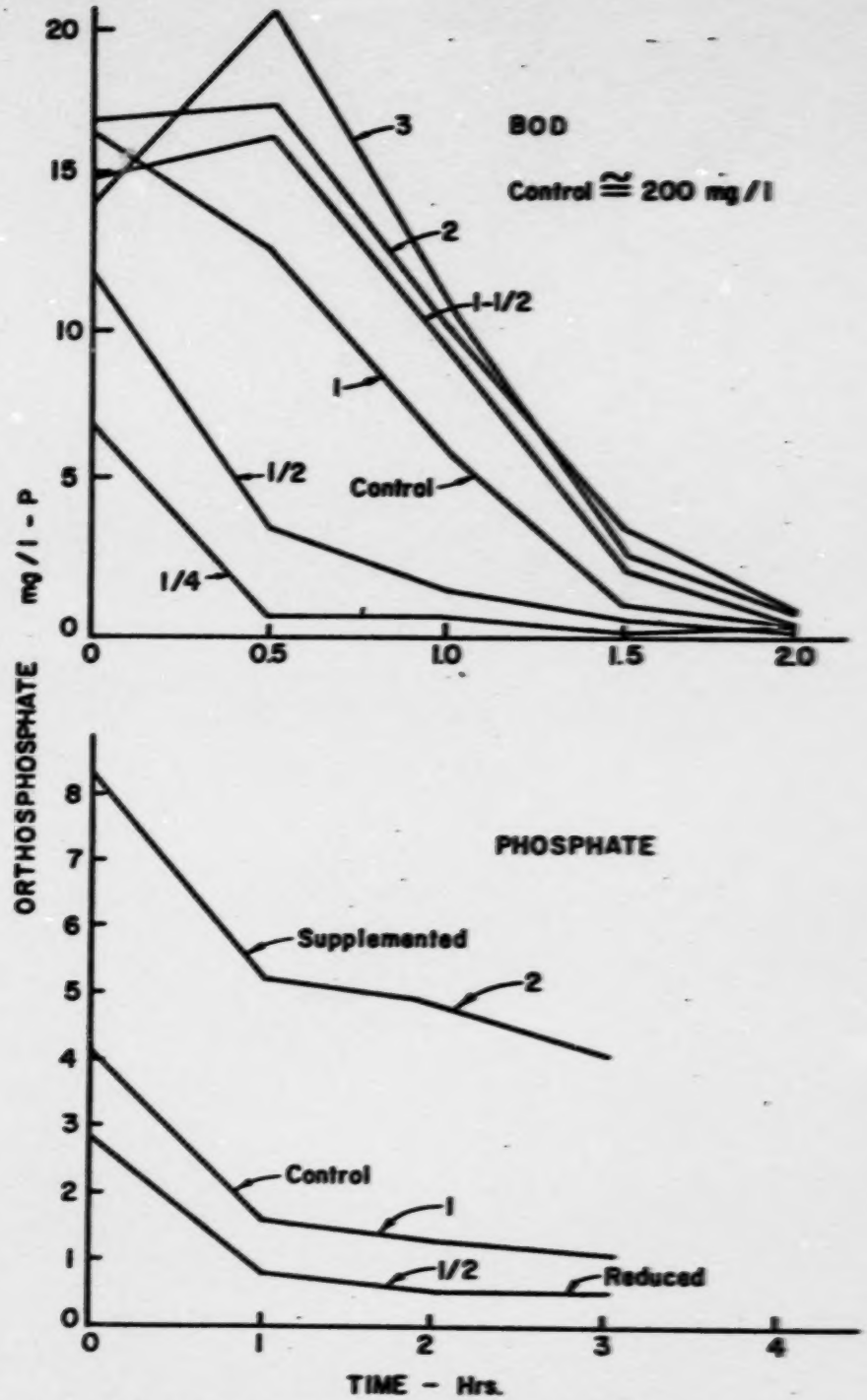

FIGURE 7 - EFFECT OF WASTE STRENGTH ON PO_4 REMOVAL

adding K_2HPO_4, and reduced by diluting with phosphate-free city water. The MLSS concentration was 3,200 mg/l.

Supplementing either phosphate or DO strength distinctly affected phosphate removal. The effects of DO and phosphate were confounded by the dilution technique. The reduction in strength was beneficial while increasing the DO over 2.0 mg/l or increasing the phosphate concentration was detrimental to phosphate removal.

The effects of air volume, sludge solids, and waste strength are shown in these experiments. The importance of some fine and aeration detention can be seen in both Figures 5 and 7. Phosphate removal being the dependent requires that all the mixed liquor be aerated for a specified time to attain maximum removal efficiency. A plug-flow tank design with controlled maximum waste flow fulfills the requirement.

Aeration tank studies in the West Plant gave indication of the DO and phosphate removal relationship. Phosphate removal did not occur in the tank with 0.2 to 0.4 mg/l of DO, but 70 percent removal occurred in the tank with 1.5 to 3.1 mg/l of DO. Each of the nine tanks was set to receive equal amounts of waste, return sludge, and air, and all tanks had equal values. These results demonstrated the efficiency of diffuser and the effect of DO on phosphate removal.

Monitoring of two parallel tanks at Hillsboro also demonstrated the relationship of air and the time dependence of phosphate removal. Figure 8 is a plot of phosphate and DO concentrations versus

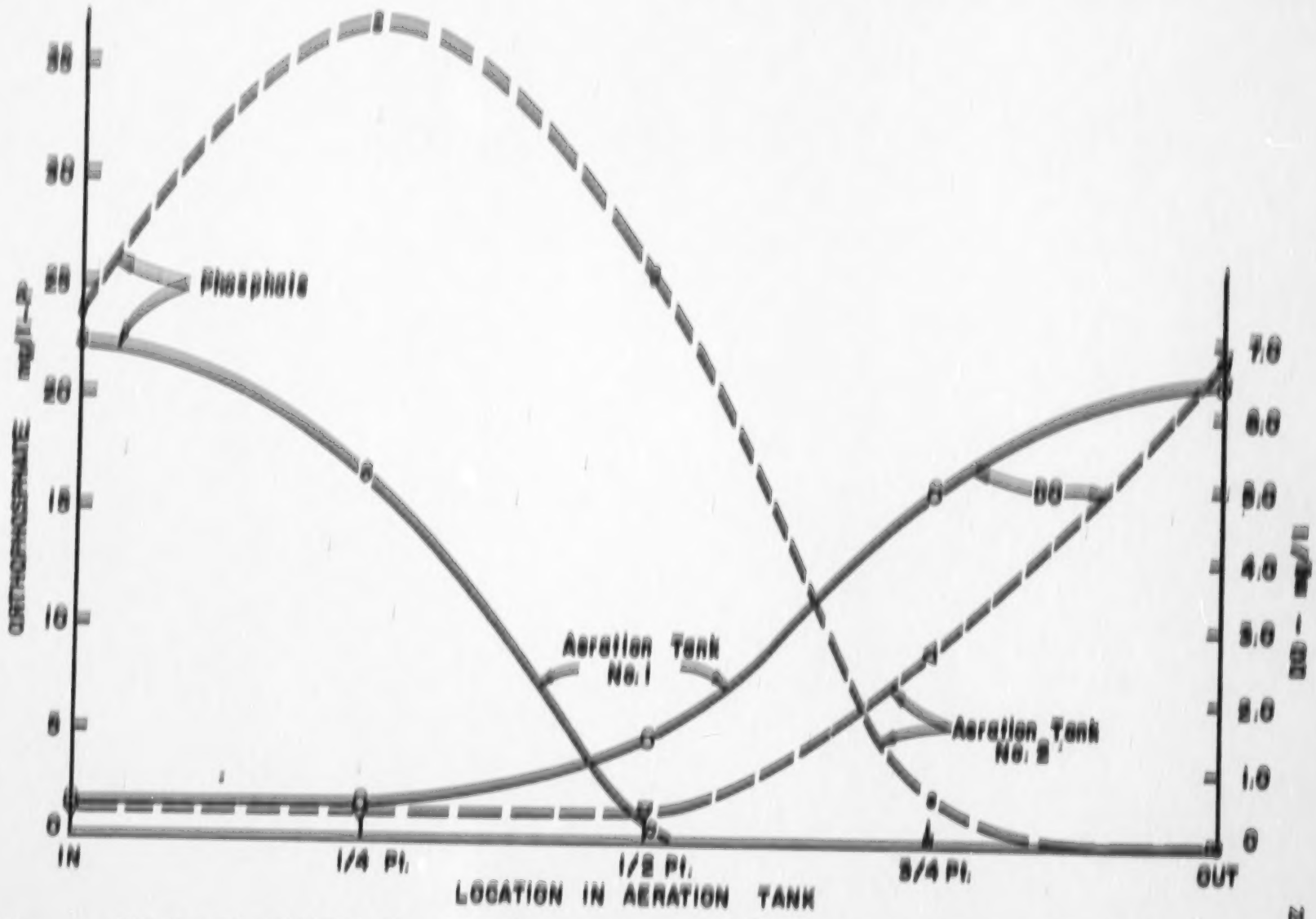

FIGURE 8 - PHOSPHATE REMOVAL IN AERATION TANKS - BALTIMORE, MARYLAND

TABLE V. SUMMARY OF 10-DAY PROFILE ON AERATION TANKS
MEAN VALUES AT HIGH AND LOW REMOVALS (mg/l)

	Amarillo		Baltimore		Fort Worth		San Antonio	
AERATION TANK	High	Low	High	Low	High	Low	High	Low
Removal (%)	99	58	99	72	92	57	93	48
O-PO_4 Inlet	19.4	28.6	24.3	26.0	8.6	12.7	18.0	18.4
O-PO_4 Outlet	0.2	12.1	0.2	7.4	0.7	5.5	1.3	9.6
PRIMARY EFFLUENT								
BOD	175	303	202	243	118	183	152	212
O-PO4	10.5	12.2	8.8	9.3	4.2	7.9	5.6	7.3
T-PO_4	16.7	19.6	14.2	16.7	7.4	13.0	7.4	14.0
MIXED LIQUOR								
DO Outlet	2.4	1.7	3.1	1.1	--	--	--	--
BOD (lb./lb/day)	.34	.57	.35	.36	.26	.46	.28	.64
Air ($ft.^3$/lb. BOD)	1360	640	790	660	1230	745	2440	1130

concentrations in the primary effluent, the BOD loading and the $O\text{-}PO_4$ concentration at the tank inlet all decreased when phosphate removal increased. The DO at the tank outlet and the air applied increased when phosphate removal increased. Statistical hypothesis tests were made on DO concentrations at the outlet and found to be significantly different at the 0.05 level between high and low removals. The data presented indicate the variation in magnitude of these parameters during periods of high and low removals. During high removal, BOD concentration and loading ranged from 118 to 202 mg/l and from 0.26 to 0.35 lbs./lb. of MLSS/day.

The importance of further specifying the parameters controlling phosphate removal in the aeration tank has been recognized, and an 18-month, $250,000 investigation has been initiated at Baltimore for this purpose.

Reaeration Tanks

The East Plant in San Antonio and the Village Creek Plant in Fort Worth were both conventional activated sludge plants modified to use approximately one-fourth of the aeration tank volume for reaeration of return sludge.

Total phosphate removal in the Village Creek Plant was presented in Table II. Under desired operating conditions, the aeration tanks obtained phosphate removal exceeding 90 percent during both investigations. The overall lower removals were the result of phosphate release in the final clarifier. The use of sludge reaeration did not prevent removal in the plant or hinder near maximum removal in the aeration tanks.

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Sludge Disposal

The waste activated sludge is the vehicle for phosphate disposal. In removing plants, phosphate content of the suspended solids has been as high as 11 percent. Sludge disposal at 4 of the 5 removing plants has been to lagoons. At Baltimore, the sludge is returned to the primary clarifiers from which 85 percent goes to a trickling filter plant, and the remainder is recycled to the activated sludge plant.

Gravity thickeners at the Fort Worth, Amarillo, and San Antonio-West Plants processed the waste sludge. Detention in a gravity thickener could produce conditions causing release of phosphate from the sludge. Since the overflow from the thickener was returned to the plants, its phosphate content was measured. The total phosphate was 6.4, 3.1, and 22.6 mg/l-P in San Antonio, Fort Worth, and Amarillo, respectively. These concentrations and the limited flows make the recycled stream insignificant. A gravity sludge thickener with recycled overflow properly operated can be used on the waste sludge without destroying the phosphate removal process.

The Fort Worth Plant anaerobically digests the thickened sludge before discharging it to lagoons. The concentrations of the digester discharge and the thickened sludge are the same--about 1,200 mg/l-P. The return of digester supernatant to the removal system would recycle most of the phosphate and destroy the process by eliminating the disposal vehicle.

CONCLUSIONS

Some activated sludge plants can, on a sustained basis, average 80 percent phosphate removal on a municipal (domestic-industrial) waste. Equivalent removal is possible on most municipal wastes by a properly designed and operated activated sludge process.

Phosphate balances at five plants established high phosphate removal by the activated sludge process with waste sludge as the vehicle for phosphate disposal.

Design and operation of the activated sludge process are related to phosphate removal efficiencies; control of these parameters can result in greater than 80 percent removal.

Phosphate removal by primary settling is insignificant to the phosphate reduction in the activated sludge process; reduction is accomplished in the aeration tank by incorporation with the sludge solids.

Phosphate removal in the aeration tank is affected by concentrations of suspended solids and dissolved oxygen in the mixed liquor and the biochemical oxygen demand and phosphate applied to the tank. The combination of these aeration tank parameters giving maximum phosphate removal varies between plants but have been found as follows:

MLSS: $\geq$1,200 mg/l

DO: $\geq$2.4 mg/l at tank outlet

BOD: 118 to 202 mg/l in waste input
0.26 to 0.35 lbs./lb. MLSS/day

O-PO_4: 4.2 to 10.5 mg/l-P in waste input

Phosphate reduction in the aeration tank is a time dependent reaction requiring a modal detention of 2.5 hours or more.

In the final clarifier, phosphate reduction is maintained by maximizing solid-liquid separation and minimizing anaerobic conditions with high sludge return rates, low SVI, and high dissolved oxygen content.

Both sludge reaeration and gravity sludge thickening can be successfully incorporated in the phosphate removal-activated sludge process.

The waste activated sludge releases its phosphate content under anaerobic conditions. Neither the waste activated sludge nor its digested supernatant can be recycled without eliminating the phosphate disposal vehicle and destroying the removal process.

ACKNOWLEDGMENTS

The investigations summarized in this paper are the results of many research personnel at the Robert S. Kerr Water Research Center who can best be acknowledged by referencing the detailed reports which they authored.

Without the effort and dedication of the listed authors and the supervisory personnel at the plant monitored, this paper would not have been possible.

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